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Experimental Evaluation of Mechanical Properties of Stereolithography, Selective Laser Sintering, Fused Deposition Modeling and Other Additive Manufacturing Methods

K. Shilpa[1], D. V. Paleshwar[2], Sainath Kasuba[3]
[1]Student, Dept. of Mechanical Engineering, Sreyas Institute of Engineering & Technology, Hyderabad, India
[2]Asst. Prof., Dept. of Mechanical Engineering, Sreyas Institute of Engineering & Technology, Hyderabad, India
[2]Assoc. Prof., Dept. of Mechanical Engg., Sreyas Institute of Engineering & Technology, Hyderabad, India

***Abstract*—Additive Manufacturing (AM) or 3D Printing have become very popular in industry and academia for prototyping or for small scale production. They are being widely accepted as replacement for conventional methods. It is imperative to fully understand the properties and characteristics of the parts manufactured using additive manufacturing. It is very important to understand the mechanical properties of products manufactured through various additive manufacturing processes like Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM) and Polyjet. In this project we propose to evaluate mechanical properties such as Dimensional Accuracy, Tensile property and Shore Hardness of components manufactured by various additive manufacturing techniques as per ASTM D638-10 type iv standard. Each additive manufacturing process and its process parameters are studied in detail along with comparison of mechanical properties of the final components. Project would give a detailed overview of advanced additive manufacturing processes.**

***Index Terms*—Additive Manufacturing, ASTM D638-10 type iv standard, Dimensional Accuracy, FDM, Polyjet, SLA, SLS, Tensile property, Shore Hardness.**

I. Introduction

Additive Manufacturing (AM) is a process which produces a part layer-by-layer of a material whether the material is plastic, metal, concrete or one day…..human tissue. This technology has also been referred to as layered manufacturing, rapid prototyping, and rapid manufacturing. Additive Manufacturing automatically generates physical objects directly from 3D CAD data. The Additive Manufacturing equipment reads in data from the CAD file and lays downs or adds successive layers of liquid, powder, sheet material or other, in a layer-upon-layer fashion to produce a 3D object, unlike conventional methods, where material is removed to obtain the final object.

In this project, the experimental evaluation of mechanical properties such as dimensional accuracy, tensile property and shore hardness on Selective Laser Sintering (SLS), PolyJet, Fused Deposition Modeling (FDM), and Stereolihography (SLA) will be discussed in detail. A set of specimen of three build orientations (horizontal, side, vertical) on each of these additive manufacturing processes according to ASTM D638-10 type iv standards.

II. Literature Survey

Nowadays, with the fast development of rapid prototyping technologies: more available materials, with various mechanical properties to meet a variety of applications, and higher accuracy of parts produced, rapid prototyping technologies have been used for fabrication of functional parts and tooling. As rapid prototyping parts are made by additive processes, they may have properties that are quite different from parts that are made by conventional manufacturing processes. It is difficult to directly compare the many properties of rapid prototyping parts, as these depend not only on the material being used, but also on the direction in which the property is being measured. In this study, the properties: (1) dimensional accuracy, (2) tensile property, (3) Shore hardness were investigated.

According to the previous work and literature source related to these topics, it is observed that the dimensional accuracy of an additive manufacturing product is influenced by a specific rapid prototyping technique used, the material chosen, and the operating parameter values. Due to different processes and materials used in rapid prototyping technologies, parts differ in their tendency to shrink or deform. The accuracy data in this paper was obtained from technical publications and from company literature. There was no comparative information available for different build orientations.

It is observed that the shrinkage of the Stereolithography (SLA) epoxy was significantly less than the Selective laser sintering (SLS) plastic material, and the small shrinkage of Stereolithography (SLA) resins was simple to predict and easy to control. It is observed that the choice of deposition strategy plays an important role in the Fused Deposition Modelling

(FDM). Different deposition strategies may cause different performance in mechanical properties.

III. Methodology

The investigations of dimensional accuracy and tensile properties testing for three build orientations are provided in this paper. Furthermore, Shore hardness for these samples are also available in this study.

A. Experimental Scheme

Table I shows the manufacturers and models by this prototyping systems. The technical characteristics can be found in the literature. In determining the dimensions of the test specimens, a digital caliper was used, with the measurement range 0-150/0.01 mm. The ADMET eXpert 2611 universal testing system was used to test the tensile properties. Tests were performed at a temperature of 72°F with air-conditioning. The specimens has been chosen for investigating the Shore hardness.

TABLE I
MANUFACTURER AND MODEL

System	Manufacturer	Model
SLS	EOS	Default Standard calibration for PA2200 Z-Axis = 0.100 mm
Polyjet	Objet	Default Print mode = High Quality Z-Axis = 0.016 mm
FDM	Dimension	Default Model interior fill = Sparse - High density Support Fill = Sparse Z-Axis = 0.01 inch (0.254 mm)
SLA	Form 2	Default Print mode = Z-Axis = 0.01 inch (0.254 mm)

B. Materials and Sample Preparation

TABLE II
MATERIAL AND MACHINE SETTING

System	Material	Machine Setting
SLS	PA 3200 (polyamide 12)	Default Standard calibration for PA3200 Z-Axis = 0.100 mm
Polyjet	Tango Black	Default Print mode = High Quality Z-Axis = 0.016 mm
FDM	ABS plastic	Default Model interior fill = Sparse - High density Support Fill = Sparse Z-Axis = 0.01 inch (0.254 mm)
SLA	ACCURA 60	Default Print mode= Z-Axis = 0.01 inch (0.254 mm)

Materials used in this study were commercially available Nylon, ABS plastic, and resign. Table II shows the materials and the machine settings that were used in the specified rapid prototyping systems. The materials that were used in this research were the most popular in the current commercial marketplace. The machine settings were also listed in Table II. The test specimens were fabricated by these four additive manufacturing processes in three build orientations as shown in Table II, and the dimensions conformed to ASTM D638-10 Type IV.

C. Shape of Test Specimen

The tensile properties of rigid and semi-rigid plastics were determined according to the ASTM D638-10 standard, and the Type IV specimen was used when directly comparing between different rigid materials. Fig 1 presents the dimensions of the tensile test specimen and the location of these dimensions and the shape of the test specimen for tensile testing. A minimum of five test specimens are recommended by the standard. The testing speed for the specimen ASTM D638 Type IV is 5 ±25% mm/min, and the higher speeds 50 ±10% mm/min and 500 ±10% mm/min were used, which attains rupture within 1/2 to 5-min testing time.

ASTM D638-10 Type IV	Dimensions (mm)
W – Width of narrow section	6
L – Length of narrow section	33
WO – Width overall, min	19
LO – Length overall, min	115
G – Gage length	25
D – Distance between grips	65
R – Radius of fillet	14
RO – Outer radius	25
T – Thickness	4

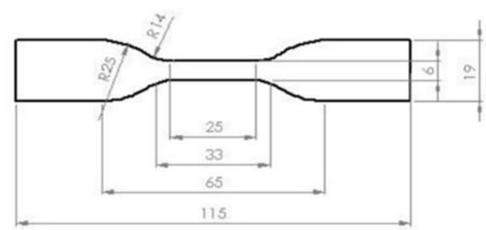

Fig. 1. Dimension and shape of test specimen

D. Dimension Measurement

Four ASTM D638 Type IV specimens were made in each of three build orientations (Horizontal, Side, and Vertical). There are four measurement points: width of narrow section (W), width overall (WO), length overall (LO), and thickness (T) on each specimen as shown in Figure 1. Dimension of the specimen was measured by a Pittsburgh digital caliper with the measurement range 0-150/0.01 mm. The measurements were done on each measurement point, and the values were then recorded. For the measurement point of width overall, both side on each specimen were measured, and the values were then recorded. For the measurement point of thickness, two ends and middle on each specimen were measured, and then the values were recorded. The average values and standard deviation of each measurement point for specified build orientations and rapid prototyping systems were then calculated.

E. Tensile Property Testing

ASTM Type IV specimens were made in each of three build orientations (Horizontal, Side, and Vertical) in each rapid prototyping systems. Tensile tests were performed on a universal testing machine (ADMET eXpert 2611) equipped with a 10 kN load cell. All the tests were conducted at the same temperature of 72°F.

For determining the tensile properties the test specimen is clamped by the jaws of the test machine as shown in Figure 8 and extended with force, at testing speed 5 mm/min as defined by ASTM D638-10 standard. The reported data are the average values from a specimen.

F. Shore Hardness

Horizontal build orientation was chosen to create specimens in the four rapid prototyping systems for investigating the Shore hardness. Two specimens were made in each of the four rapid prototyping systems. Hardness of elastomers and most other polymer materials (Thermoplastics, Thermosets) is measured by the Shore D scale. The durometer, Pacific Transducer Corp. Model 409 ASTM Type D, as shown in Figure 2, was used to measure the Shore hardness. The durometer is a hand-hold device consisting of a needle-like spring-loaded indenter, which is pressed into the test specimen surface, and the penetration of the needle is measured directly from a scale on the device in terms of degrees of hardness. There were six measurement points (three on each side) on each specimen as shown in Figure 3. The measurement was done three times in each measurement point and the average value was then recorded.

Fig. 2. Shore D Scale Durometer

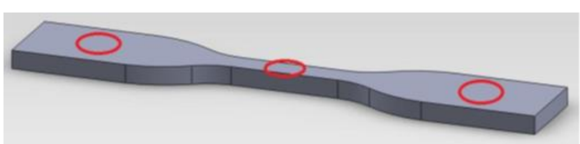

Fig. 3. Measurement points on test specimen

IV. Results and Discussion

A. Dimensional Accuracy

Before doing tensile property test, all specimens were measured to investigate their dimensional accuracy. Dimensional accuracy for each measurement point and each fabricated orientation from specified rapid prototyping systems was also presented in the following sections. Equation 1 shows how to calculate Dimension Change Rate. Equation 2 shows Dimensional Accuracy which is the absolute value of dimension change rate from Equation 1. Measured results and the standard deviations were presented in the following sections.

$$Dimension\ Change\ Rate\ (percent) = [Measured\ value\ (mm) / Desired\ value\ (mm) - 1] \times 100 \quad (1)$$

$$Dimensional\ Accuracy\ (percent) = [Measured\ value\ (mm) / Desired\ value\ (mm) - 1] \times 100 \quad (2)$$

The Table III shows the measured dimensional accuracy percentage values for the additive manufacturing processes and Fig. 4, shows the comparison of dimensional accuracy in a chart.

The Fig. 4, shows the summary dimensional accuracy of four measurement points in each rapid prototyping system. Considering different rapid prototyping systems, PolyJet performs with the best dimensional accuracy. Considering the build orientations, Horizontal is more accurate than Side and Vertical in PolyJet, FDM, and SLA, with the exception of the SLS system. In SLS, the Vertical build orientation has more dimensional accuracy than others. Table III tabulates the summary dimensional accuracy in these four rapid prototyping systems.

TABLE III
Dimensional Accuracy Values

System	Build Orientation	Dimensional Accuracy (%)
SLS	Horizontal	2.2239
	Side	1.5837
	Vertical	0.6293
Polyjet	Horizontal	0.4257
	Side	1.2767
	Vertical	1.7147
FDM	Horizontal	1.1645
	Side	2.3149
	Vertical	2.2445
SLA	Horizontal	2.5702
	Side	3.9541
	Vertical	2.8746

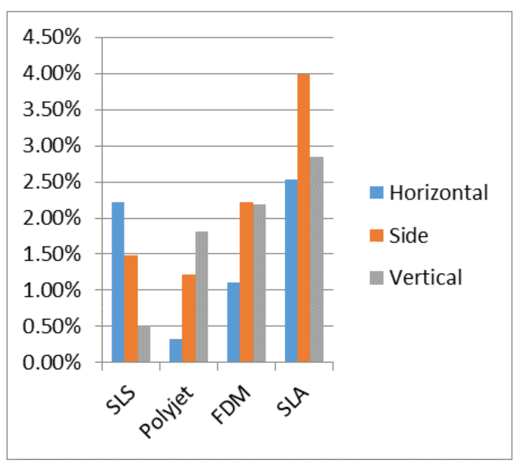

Fig. 4. Dimensional accuracy comparison

B. Tensile Property

From the tasks performed, the results obtained from tensile testing are displayed in this section. Test specimens were fabricated with three build orientations (Horizontal, Side and Vertical) in four rapid prototyping machines (SLS, PolyJet, FDM, and SLA). For each type of the specimen, five to eight replications were fabricated and tested. Tensile testing was performed on the specimens using a universal testing machine: ADMET eXpert 2611. The ADMET software was used to calculate the Tensile Strength, Elongation, and Elongation at break of each test sample. For comparisons of tensile testing as a function of direction and method of creation, the bar chart showed in Fig. 5 was constructed. Figure 18 displays the average value of the Tensile Strength respectively of the specimens produced under the different rapid prototyping systems and each build orientation.

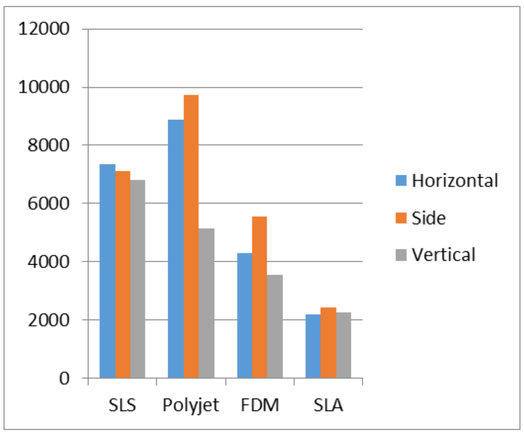

Fig. 5. Tensile strength

It can be seen that the difference in build orientations within the different RP systems does affect the tensile strength of the specimens. Considering effect of using different RP systems, it was found that PolyJet gave the greatest value of tensile strength, followed by SLS, FDM, and SLA, respectively. Considering build orientation, the samples created in Side orientation in PolyJet, FDM, and SLA showed the greatest tensile strength compared with Horizontal and Vertical samples. In the SLS system, the specimens created in Horizontal orientation have the highest tensile strength. Comparing the specimens built in three orientations in the SLS and SLA systems only slightly varied in tensile strength. Comparing Side and Vertical orientations in the PolyJet and FDM systems, a significant difference in tensile strength occurred.

In ASTM D638, the following definition is given: Percent Elongation — Percent elongation is the change in gage length relative to the original specimen gage length, expressed as a percent. Percentage Elongation at Break — Calculate the percentage of elongation at break by reading the extension (change in gage length) at the point of specimen rupture. Divide that extension by the original guage length and multiply it by 100.

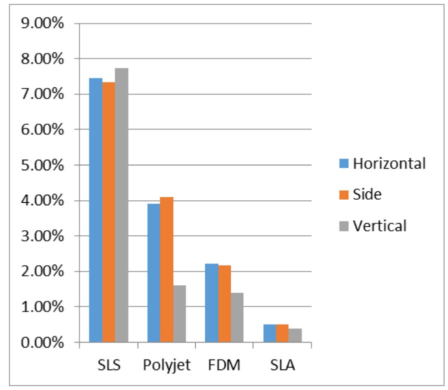

Fig. 6. Elongation (%)

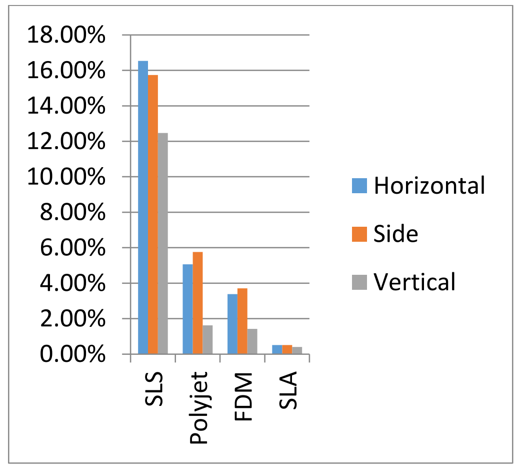

Fig. 7. Elongation at break (%)

The Fig. 6 and Fig. 7 show the Elongation and Elongation at Break, respectively, of the samples produced under the different RP systems and build orientations. It can be seen from the figures that there is a significant difference in Elongation and Elongation at Break between samples produced in SLS and the other three systems. The raw material (PA 3200 Balance 1.0) used in SLS system is based on polyamide 12 which may account for the higher elasticity. However, Elongation and Elongation at Break are different samples created in different orientations in the same RP system. Considering build orientations, the samples created in Horizontal and Side have a greater Elongation and Elongation at Break in PolyJet and FDM compared with the Vertical orientation. The specimens of Vertical build orientation resulted in the lowest Elongation and Elongation at Break because the tensile loads were resisted only by the bonding between layers, and not the layers themselves.

C. Shore Hardness

Hardness of hard elastomers and most other polymer materials (Thermoplastics, Thermosets) is measured by the Shore D scale. The scale resulting in the values between 0 and 100, with higher values indicating a harder material.

Shore hardness is a measure of the resistance of a material to penetration of a spring loaded needle indenter. Two specimens were created in the Horizontal build orientation in each RP system: SLS, PolyJet, FDM, and SLA. The reason to choose

Horizontal build orientation was the shortest machine duration compared with Side and Vertical. For the Shore Hardness investigation, the independent variable was the specified rapid prototyping system and its relative material used, and the dependent variable was the Shore Hardness. The independent variable, build orientations, was not included in this investigation. There are three measured points on two long planes; total six measured points in one specimen. Table 16 shows the average measured values and standard deviations. The order of hardness is PolyJet > SLA > FDM > SLS. The highest scale of Shore hardness appeared in the test specimens created by PolyJet technology with 83.73, while the lowest scale of Shore hardness can be seen in the samples created by SLS technology with 77.69.

TABLE IV
SHORE HARDNESS

System	ASTM D2240 Type D Scale	Standard Deviation
SLS	76.2434	1.7237
Polyjet	83.7365	0.7975
FDM	77.6964	2.2453
SLA	81.4534	1.2978

V. CONCLUSION

The results obtained in this project include dimensional accuracy and tensile properties for different build orientations, and the Shore hardness between different rapid prototyping systems: SLS, PolyJet, FDM, and SLA. We can conclude that different build orientations had a significant effect on dimensional accuracy and tensile properties in the SLS, PolyJet, FDM and SLA. Considering dimensional accuracy in different build orientations, Horizontal was more accurate compared with Side and Vertical in the PolyJet, FDM, and SLA, with the exception of the SLS system. In the SLS, Vertical build orientation was more accurate compared with horizontal and Side. Considering tensile properties in different build orientations, Side build components were the strongest compared with parts created in Horizontal and Vertical build orientations in the PolyJet, FDM, and Polyjet, except the SLS technology. In the SLS technology, Horizontal build orientation was the strongest compared with others.

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